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RESEARCH ARTICLE

Laser Plasma Interaction in Laser-based Accelerators with Self-focusing of Laser

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ABSTRACT: Extreme light intensities can be produced by high-power lasers, but the requirement for huge beam diameters to prevent damage to optical components prevents future development. Plasma can support extremely brilliant radiation and can be used to create and manipulate light without causing damage to solid materials. In order to create extremely high acceleration gradients for accelerators, relativistic plasma waves must be produced by powerful laser or electron beams in low-density plasmas. One of the methods is the wakefield accelerators. In this article, the basic characteristics of laser propagation and plasma wave excitation are discussed in the framework of laser-driven wakefield acceleration. The self-focusing behaviour of a Gaussian laser beam travelling through an inhomogeneous axial plasma is investigated.

KEYWORDS: Laser accelerators, self-focusing, plasma, wakefield

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INTRODUCTION

The researcher's quest to explore physics on the lowest scale, which is made up of the fundamental particles and forces, the investigation seeking for the origin of matter and the cosmos needs establishing the greatest energy state. With today's high-energy colliders delivering energies of 100 GeV, particle accelerators have mostly served as tools as microscopes to explore the tiniest realm of nature. We are already entering a new energy regime of TeV-PeV. Again, a variety of sciences have made use of high energy electron accelerators having beam energies in the GeV range to produce short wavelength radiations. High power radio frequency (RF) technologies are the foundation of current high energy accelerators, which are capable of accelerating charged particles with electric fields up to 100 MV/m at maximum. This limit can only be achieved steadily in metallic electromagnetic cavities owing to electrical surface heating and breakdown. [1]

Tajima and Dawson first presented the idea of laser-driven plasma-based accelerators [2].The two scientists proposed utilizing plasma produced by a laser to accelerate particles, mostly electrons but also protons and other charged particles (ions), in 1979. One of the four basic forms of matter, along with solid, liquid, and gas, is plasma. To produce plasma, a powerful laser is directed towards a target, like a gas (for accelerating electrons) or a fine material (for accelerating protons). When the strong laser beam strikes the solid or gaseous substance, the atoms are immediately ionized. This implies that the electrons are freed from their bonds to the atomic nuclei. The term "plasma" refers to this ionized condition. The field of laser-matter interaction has made significant strides in recent years with the advent of powerful short pulse laser. Strongly ionized plasma is created as a result of the contact, which manifests remarkable group effects. High-power laser pulse interactions with gas jet targets are particularly significant. This has a close relationship to plasma-based accelerators, which can withstand acceleration gradients of up to 1 GV/cm in size. This gradient is nearly four orders of magnitude larger than in traditional accelerators, hence laser-based accelerators hold out hope for the replacement of bulky RF linear accelerator (linacs) with compact apparatus. The fundamental benefit of a plasma-based accelerator is that because the plasma is already "broken down," it can tolerate accelerating electric fields that are several orders of magnitude stronger than those of traditional devices, which suffer from waveguide structure failure [3-10]. It is now possible to produce intense gamma rays and

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electron positron pairs by using the very energetic electrons created by laser-driven accelerators [11-14]. The production of gamma rays is an essential issue in the generation of electron positron pairs. The energetic electrons can generate gamma rays via Bremsstrahlung. Therefore, the laser's ability to produce MeV electrons is crucial. Significant advancements in laser-based electron acceleration have been accomplished during the previous three decades. The laser wake field accelerator is the most promising approach in this area [15-18]. In a laser wake field accelerator, a single laser pulse of short duration (comparable to plasma period) is employed which drives a plasma wave in the wake of the pulse. Kurz et al. [14] utilized a laser system that produces pulses with a 30 fs (FWHM) duration and an 800 nm central wavelength to demonstrate a small plasma accelerator. The electrostatic potential of the plasma wave is comparable to the pondermotive potential. This approach depends on the transformation of the transverse laser electric field energy into longitudinal plasma wave electric field energy. Through the operation of its ponderomotive force, the laser pulse stimulates a plasma wave behind it. Plasma electrons are trapped in this plasma wave and given a tremendous energy boost. Another significant matter, in the laser matter interaction, relevant to electron acceleration is the phenomenon of self-focusing. When a laser of finite transverse extent (or non-uniform intensity distribution) propagates through plasma, the electrons experience a ponderomotive force $\vec{F}_P = -\nabla\left|\vec{E}\right|^2$, directed opposite to the intensity gradient. This leads to a density depression on laser axis. The electromagnetic wave is guided and self-focused by the density depression, which increases the maximum wave amplitude. In case of an intense short pulse laser, the relativistic variation of electron mass also gives rise to non-uniform refractive index profile across the laser axis, causing self-focusing of the laser. In this present work, we have focused on the phenomenon of self-focusing of laser and the aim of this study is to investigate the influence of laser self-focusing on the laser plasma interaction. We demonstrate that when the plasma amplitude rises, the electrons' energy gain also rises.

2. Self-focusing of laser

When laser beams intensity reaches a certain level, the medium through which it travels experiences a nonlinear change in refractive index, which is referred to as self-focusing. The beam narrows due to self-concentration or self-focus brought on by this nonlinearity. We consider a laser propagating in plasma:

$$\vec{E} = \hat{x}Ae^{-i(\omega t-kz)} \quad \text{---- (1)}$$

where A is the amplitude of the laser field, ω is the frequency and k is the propagation vector of the electromagnetic field. At z=0, the field amplitude is given as $A^2 = A_{00}^2 e^{-\frac{r^2}{r_0^2}}$ where r_0 is the spot size of the laser. The permittivity in a nonlinear medium may be written as $\varepsilon = 1 - \frac{ne^2}{m\varepsilon_0\omega^2\gamma}$ where n, e and m are the net density, charge and mass of the electron, $\varepsilon_0$is the permittivity of the free space and is the γ Lorentz factor. The nonlinear permittivity now can be written as:

$$\varepsilon = \varepsilon_0 + \varphi \underset{|E|}{\rightarrow}^2 \quad \text{------ (2)}$$

where $\varphi = \frac{\omega_p^2}{\omega^2}(1-\frac{1}{\gamma})$ and $\gamma = (1+\frac{e^2|E|^2}{m^2\omega^2c^2})$ and ω_p is the plasma frequency.Using Maxwell's equation,$\nabla^2\boldsymbol{E} + \frac{\omega^2\varepsilon\boldsymbol{E}}{c^2} = 0$ and considering $\nabla^2 = \frac{\partial^2}{\partial z^2} + \frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial}{\partial r})$ and $k = \frac{\omega}{c}\varepsilon_0^{\frac{1}{2}}$, we get the parabolic equation in the WKB approximation from equation (1) as:

$$2ik\frac{\partial A}{\partial z} + \nabla^2 A + \frac{\omega^2}{c^2}\varphi A = 0 \qquad \text{----- (3)}$$

Here we take $A(r,z) = A_0(r,z)e^{iks}$ where eikonal $s = s(r,z)$. Using the equation (3) and equating the real and imaginary parts, we get,

$$2\frac{\partial s}{\partial z} + (\frac{\partial s}{\partial r})^2 - \frac{\varphi}{\varepsilon_0} - \frac{1}{A_0k^2}\left(\frac{\partial^2 A_0}{\partial r^2} + \frac{1}{r}\frac{\partial A_0}{\partial r}\right) = 0 \text{-- (4)}$$

and

$$\frac{\partial A_0^2}{\partial z} + \frac{\partial s}{\partial r}\frac{\partial A_0^2}{\partial r} + A_0^2\left(\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r}\right) = 0 \qquad \text{-----(5)}$$

To solve the equation (4) and (5), we expand s in powers of r, as

$s = s_0 + s_2\frac{r^2}{2}$.

Since the wave is symmetrical about the z axis, so no odd powers in r is taken. Putting the value of s in equation (5) we get,

$$\frac{\partial A_0^2}{\partial z} + 2s_2A_0^2 + s_2r\frac{\partial A_0^2}{\partial r} = 0. \qquad (6)$$

We introduce a function $f = f(z)$ such that $\frac{1}{f}\frac{\partial f}{\partial z} = s_2$ and using the same in equation (6) we get:

$$\frac{\partial A_0^2}{\partial z} + \frac{2}{f}\frac{\partial f}{\partial z}A_0^2 + \frac{r}{f}\frac{\partial f}{\partial z}\frac{\partial A_0^2}{\partial r} = 0. \quad \text{---- (7)}$$

We define $A_0^2 f^2 = G(r, z)$, so that equation (7) looks in a simpler form as,

$$\frac{\partial G}{\partial z} + \frac{r}{f}\frac{\partial f}{\partial z}\frac{\partial G}{\partial r} = 0 \qquad \text{----- (8)}$$

For $G = F(\frac{r}{f})$ at $z = 0$, $A_0^2 = A_{00}^2 e^{-\frac{r^2}{r_0^2}} = \frac{F(\frac{r}{f})}{f^2}$ and also for $z > 0$, $F\left(\frac{r}{f}\right) = G = A_0^2 f^2$. Therefore, in general the amplitude can be written as,

$$A_0^2 = \frac{A_{00}^2}{f^2} e^{-\frac{r^2}{r_0^2}} \qquad \text{----- (9)}$$

Since the parameter f controls the spot size of the laser beam, we define this parameter as the beam width. Using the equation (9) in (4) and substituting the value of φ in terms of amplitude and thereby equating the coefficient of r^2, equation of the parameter f can be written as:

$$\frac{\partial^2 f}{\partial z^2} = \frac{1}{k^2 r_0^4 f^3} - \varphi' \frac{A_{00}^2}{r_0^2 f^3} \quad \text{----- (10)}$$

In the weak nonlinearity approximation, the solution of the equation (10) turns out to be$f^2 = 1 + z^2(\frac{1}{R_d^2} - \frac{1}{R_n^2})$, where $R_d = kr_0^2$ is the Raleigh diffraction length and R_n is the non-linear refraction length. The beam self focuses when$R_d > R_n$.As the beam self focuses f^2decreases and the rate of self focusing becomes faster. Around the focus, the weak non linearity approximation fails and one must solve the equation (10) numerically.

3. DISCUSSION

3.1 Wake Field Excitation by A Self Focused Laser

In a laser wakefield accelerator, one laser beam of shorter pulse duration $\tau \approx 2\pi\omega_p^{-1}$is employed. The intensity of the laser pulse is large enough to cause rapid ionization of the gas in the foot of the pulse. The remaining pulse drives the plasma wave in its wake. The field of the laser pulse in the axial region$(r^2 \ll r_0^2 f^2)$ may be written as

$$\vec{E} = \hat{x} A_L(t, z) e^{-i(\omega t - kz)} \quad \text{---- (11)}$$

where $A_{L0}^2 = \frac{A_{L0}^2}{f^2} e^{-\frac{(t-\frac{z}{v_g})^2}{\tau^2}}$, $v_g$is the group velocity and τ is the FWHM of the laser. The pulse imparts an oscillatory velocity to the electrons, which couple with the magnetic field of the laser and exerts a time average ponderomotive force on electrons. If one ignores there lativistic effect, the ponderomotive force turns out to be

$$\vec{F}_P = -\frac{e^2}{2m\omega^2}\nabla\left|E_L^2\right| \qquad \text{----- (12)}$$

Again, the ponderomotive potential can be written as $\varphi_P = -\frac{e^2}{2m\omega^2}E_L^2$. This nonlinear force drives a plasma wave of potential φ. Electron response to φ andφ_P is governed by the equation of motion and equation of continuity, as

$$\frac{\partial v_g}{\partial t} = \frac{e}{m}\frac{\partial}{\partial z}(\varphi + \varphi_P) \text{ ------ (13)}$$

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial z}(n_0 v_z) = 0 \text{ -------(14)}$$

where n is density of the electrons and v_z is the z-component of the velocity of the electrons. Differentiating equation (14) with respect to t and using the equation (13), we get

$$\frac{\partial^2 n}{\partial t^2} + \frac{e}{m}\frac{\partial^2}{\partial z^2}(\varphi + \varphi_P) = 0 \qquad \text{------ (15)}$$

From Poisson's equation we can write $n = \varepsilon_0 \frac{\partial^2}{\partial z^2}\varphi$ and putting the value of ω_p in equation (15), we get

$$\frac{\partial^2 \varphi}{\partial t^2} + {\omega_p}^2 \varphi = -{\omega_p}^2 \varphi_P \quad \text{----- (16)}$$

We consider a new set of variables where $\xi = t - \frac{z}{v_g}$ and equation (16) becomes

$$\frac{\partial^2 \varphi}{\partial \xi^2} + {\omega_p}^2 \varphi = -a_{00}\frac{e^{-\frac{\xi^2}{2\tau^2}}}{f^2} \text{------ (17)}$$

where $a_{00} = \frac{{\omega_p}^2 e A_0^2}{2m\omega^2}$.

We have solved equation (17) in conjunction with equation (10) to find out the behavior of the plasma wave after the passage of the laser pulse and the effect of self-focusing on the same. We define $\eta = \omega_p \xi$ and plotted it with respect to the plasma potential φ at different Z where $Z = \frac{z}{R_d}$ is the normalized distance of propagation. Figure 1 shows that the plasma wave field acquires an oscillatory behavior after the passage of the laser pulse. With the increase of the propagation distance, a strong wakefield plasma is generated and the amplitude of the plasma increases.

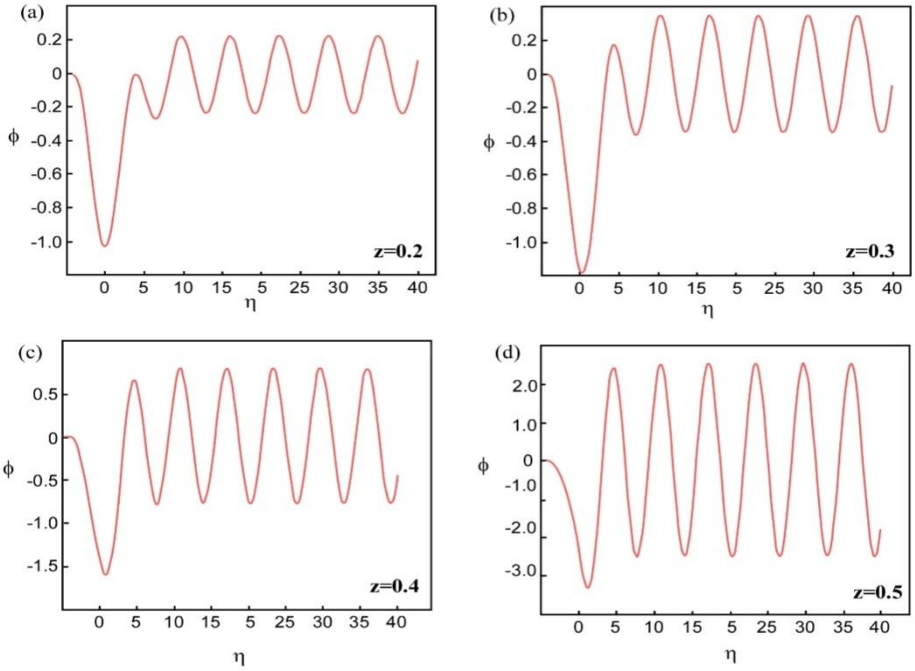

Fig.1: The wake field plasma potential with normalized distance of propagation with amplitude being (a) 0.24 (b) 0.37 (c) 0.56 and (d) 2.5 at different distance of propagation

To visualize it clearly, we have plotted the amplitude of plasma with the normalized distance of propagation. It is clearly seen that the amplitude of the plasma potential increases [see Figure 2]. Liu and Tripathi [19-20] have examined electron trapping inside a plasma wave and discussed their trajectory. They showed that the trapped electrons near the bottom of the trajectory gain large energy in course of their interaction with the plasma wave and move to the top of the curve. Accordingly, the maximum energy gain of electrons calculated by them is given by, $W_A = \frac{4eA_0c\gamma_r^3}{\omega_p}$ where $\gamma_r = (1 - \frac{\omega^2}{k^2c^2})^{-\frac{1}{2}}$. Therefore, energy gain of electrons directly depends on the amplitude of the plasma wave. Figure 2 shows that due to self-focusing the amplitude of the plasma wave is increasing. Therefore, due to the dependency of the energy gain on the amplitude of the plasma wave, the energy gain of the electrons is increased.

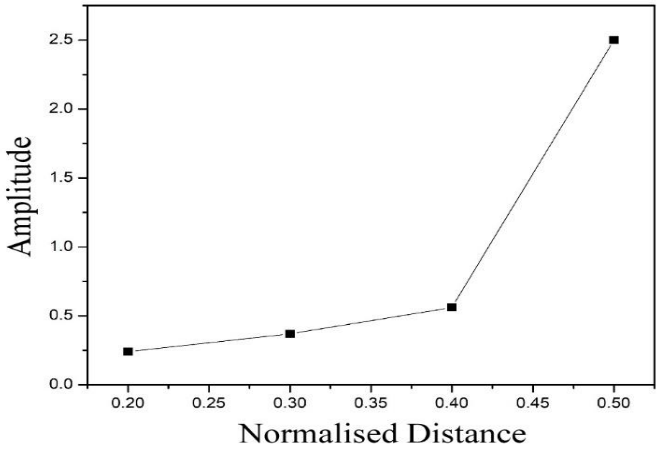

Fig.2: The amplitude of the wake field plasma potential increases with normalized distance of propagation

CONCLUSION

We have studied the high-power laser and plasma interaction and the effect of self-focusing on this interaction. The wakefield mechanism is used to increase the electron beam acceleration. The phenomenon of self-focusing has been taken into consideration to increase the amplitude of the plasma wave. Since the maximum electron beam energy gain depends on the plasma wave's amplitude, the energy gain increases. We know that in free electron laser scheme, the gamma rays are generated. A counter propagating laser interacts with the electron beam. The pondermotive force produced, retards the electrons and gamma rays are produced. Pair production is one of the most important processes by which Gamma rays interact with the matter. Further calculation of our study can show that increase in the energy gain of the electrons can increase the pair production yield. Research into plasma acceleration processes is still ongoing. Realizing that the next collider would probably be a linear electron-positron collider, researchers are putting up a unique design for constructing one [21, 22]. To boost the brightness of next linear colliders, some organizations are also creating an altogether new form of electron lens that uses plasma focusing [23].

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